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SOME RESULTS RELATED TO SPACE PROPULSION

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# SOME RESULTS RELATED TO SPACE PROPULSION*

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## ABSTRACT

An arc image oven is used in the investigation of solar energy collection. Experimental heat elements have been built. The electrostatic propulsion units use mercury ions as the working medium and have a specific impulse of 3800 sec. The rail-type plasma-gun is used to study the discharge propagation. Sliding field plasma accelerators are based on the removal of the conducting medium by Foucalt currents. The electric arc propulsion units use argon and helium as propellants, and are water cooled.

## INTRODUCTION

The general aim of electric propulsion research is the production /1** of specific impulses considerably larger than those which can be achieved with chemical fuels. Nevertheless, in view of earth satellite missions, there is a requirement for relatively moderate specific impulses, for example, on the order of 500 to 1,000 seconds. This means that one cannot neglect the simple idea of electric propulsion, such as, for example, the electrothermal propulsion unit. The latter continues to be of interest despite advanced concepts such as plasma accelerators.

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**Numbers given in the margin indicate pagination in the original foreign text.

This is the reason I feel obligated to present to you some of the results obtained at the ONERA concerning various propulsion methods now under study, without omitting any subject under investigation. I would like to add that the material I am about to discuss is only concerned with research of a fundamental nature, closer to the physics of phenomena than the technology of equipment production. I will not limit myself to a brief comparison of the regions of application inherent to each of them.

The paper consists of five parts:

- Collection and utilization of solar energy.

- Electrostatic propulsion units.

- Rail type plasmagun.

- Plasma accelerator with a sliding field.

- Electrothermal propulsion unit.

## COLLECTION AND UTILIZATION OF SOLAR ENERGY

The basic problem related to a power source for electric space propulsion is far from being solved, because the production of a nuclear reaction-electric generator group is probably quite far away. In spite of the low density (1.4 $kW/m^2$ in the vicinity of the earth), solar radiation is certainly an interesting source of energy, especially for missions in the vicinity of the orbit of the earth, or within it (Ref. 1). At the present time, it is only used on satellites for (energy) supply purposes, after being converted by means of solar panels. We may readily enumerate possibilities for its use as a means of propulsion, either by direct heating of the propulsion unit (Ref. 2) or by first converting it to electric energy (Ref. 3) by means of systems which could replace the cells of today. /2

The experimental work carried out at ONERA is at the present time limited to experiments in which a fluid is heated which is located in a cavity installed in the focus of an arc image oven (Figure 1). It consists of two parabolic mirrors 1.5 m in diameter. It is also installed in the focus of such a mirror exposed to sunlight, and the direction to the sun is maintained (Ref. 4). The problems

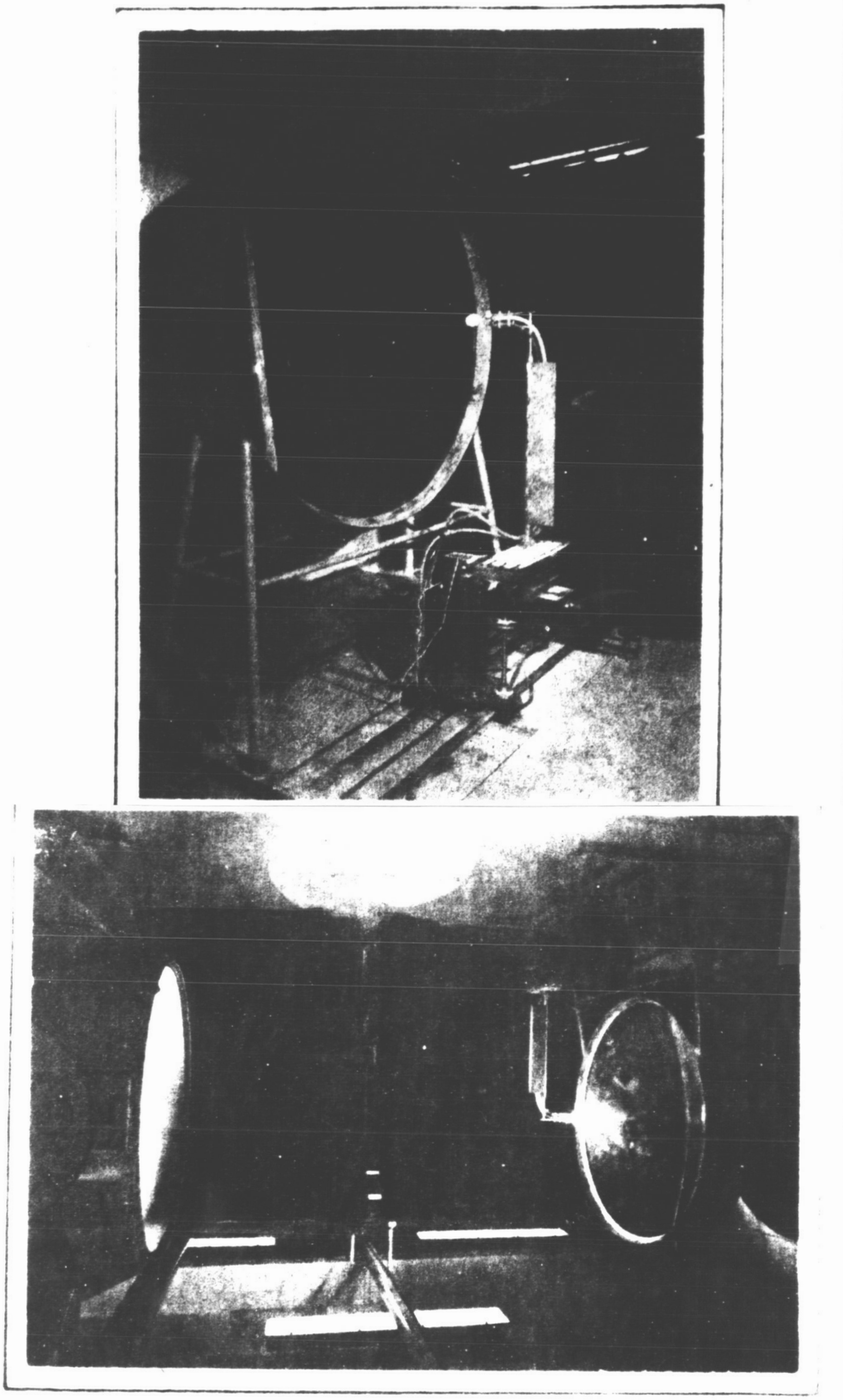

Figure 1

Arc Image Oven

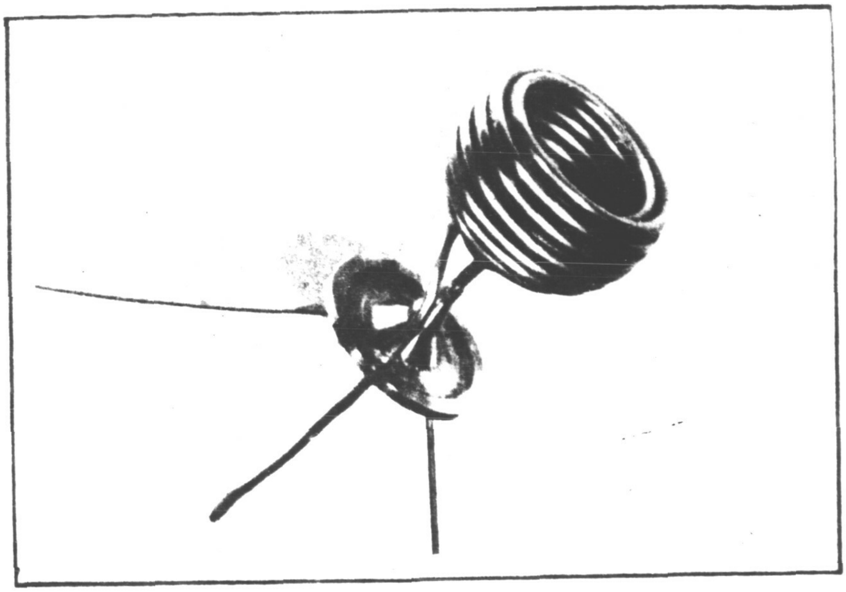

Figure 2

Heat Element for Solar Receiver

encountered are to a large extent technological due to the high temperature which must be investigated (2,000°K). The propellant used is helium, which in principle is less interesting than hydrogen because the molecular mass is larger. However, it is easier to handle and completely neutral with respect to metals at high temperatures. The heating can easily be directly measured by means of a thermocouple placed in the settling chamber or by studying the sonic blocking of the ejection nozzle (Ref. 5). Figure 2 shows an example of an experimental heat element, which consists of a platinum coil rolled into a quasi-spherical form, which can be introduced into a receiving cavity. Configurations with multiple cavities, which assure a stage-wise correction of the radiation at increasing temperatures, are presently being studied in order to increase their output, especially when the mirrors are not perfect. The cavity which contains the coil was designed so as to obtain thermal transfer with optimum output. The losses due to radiation were reduced by taking advantage of the luminescent flux, especially when the focusing is not perfect.

A true study of the receiver can only be made using solar radiation, because the electric arc results in an imperfect collimation of the bundle projected towards the receiving mirror, and there is a mediocre definition of the image point in the focal plane.

The experiments using the arc image oven are only preparatory to those which will be carried out at the Solar Energy Laboratory at Montlouis. The focus of the mirror will control the apparent displacement of the sun.

Using hydrogen, one can achieve a specific impulse on the order of 800 to 900 seconds in the vicinity of the earth. The hydrogen can easily be stored over several days, which is sufficient to obtain an orbit having a large eccentricity, for example.

In addition to this possibility for the direct utilization of thermal energy, it seems interesting to consider photo-voltaic conversion into electrical energy by using a smaller concentration of the radiation, for example 100 to 200, instead of several thousand. As an example, Figure 3 shows several types of solar probe missions which may be carried out in the future and which use the radiation energy of the sun. They will be especially interesting if they take place in regions where the density of the radiation reaches 5 kW/m2.

The mass power which can be achieved will be on the order of 100 electric watts per kg, using photo-voltaic conversion, thermionic conversion or thermodynamic cycle conversion. The choice of the electric energy source will be made on the basis of its ability to adapt to mercury ion propulsion systems or even a plasma accelerator.

## ELECTROSTATIC PROPULSION UNITS /3

The motor studied at the ONERA (Ref. 6) consists of a mercury ion source of the classical Kaufman type, fed by a mercury heat element which is followed by an electrostatic optical system. The latter consists of a screen grid and an accelerating grid (Figure 4). I will briefly recall the principle involved.

The mercury vapor is subjected to the bombardment of electrons emitted by an axial filament and accelerated by a radial electric field. A longitudinal magnetic field is produced by a coil which surrounds the source by elongating and curbing the trajectories of the electrons inward. Its purpose is to increase the probability of an encounter

| Method of Conversion | Power kW | At Present in Earth's Orbit | Objective at 0.5 AU | | Adaptation | Specific S | Maximum m/s$^2$ | Obtained from an Orbit 0.5 (AU) | |
|---|---|---|---|---|---|---|---|---|---|
| | Thermal | | | | | | | | |
| Heliothermal (Direct Heating of the Propellant) | 10 to 20 | | | Thermal $H_2$ Reactor | | 800 to 900 | $5.10^{-3}$ to $10^{-2}$ | 0.2 | 10 (operation) 85 (total) |
| | Electric | | | | | | | | |
| Photo-Voltaic | 20 to 30 | 33 | 100 | Electrostatic Heavy Ions | HT Coupling | 1500 to 4000 | $4.10^{-3}$ | 0.3 Impulse | 46 (oper.) 210 (total) |
| | | | | $Hg^+$ Ions | | 4000 | $1.10^{-3}$ | 0.15 4 Impulses or more | 180 (oper.) 500 (total) |
| Thermo-ionic | 1 to 10 | 15 | 100 | Electrothermal + Magnetic Acceleration | | 1000 to 2000 | $4.10^{-3}$ | 0.3 1 Impulse) | 46/210 |
| | | | | | BT Coupling | 2000 | $1.10^{-3}$ | 0.15 4 Impulses | 180/500 |
| Turbo-mechanical | 15 to 100 | 40 Rankin Hg 15 Brayton | 125 Rankin K.Rb | Electrothermal + Magnetic Acceleration | BT Rectifier | 1000 to 2000 | $4.10^{-3}$ | 0.3 1 Impulse | 46/210 |
| | | | | | | 2000 | $1.10^{-3}$ | 0.15 4 Impulses | 180/500 |

Figure 3

Examples of Solar Probe Missions

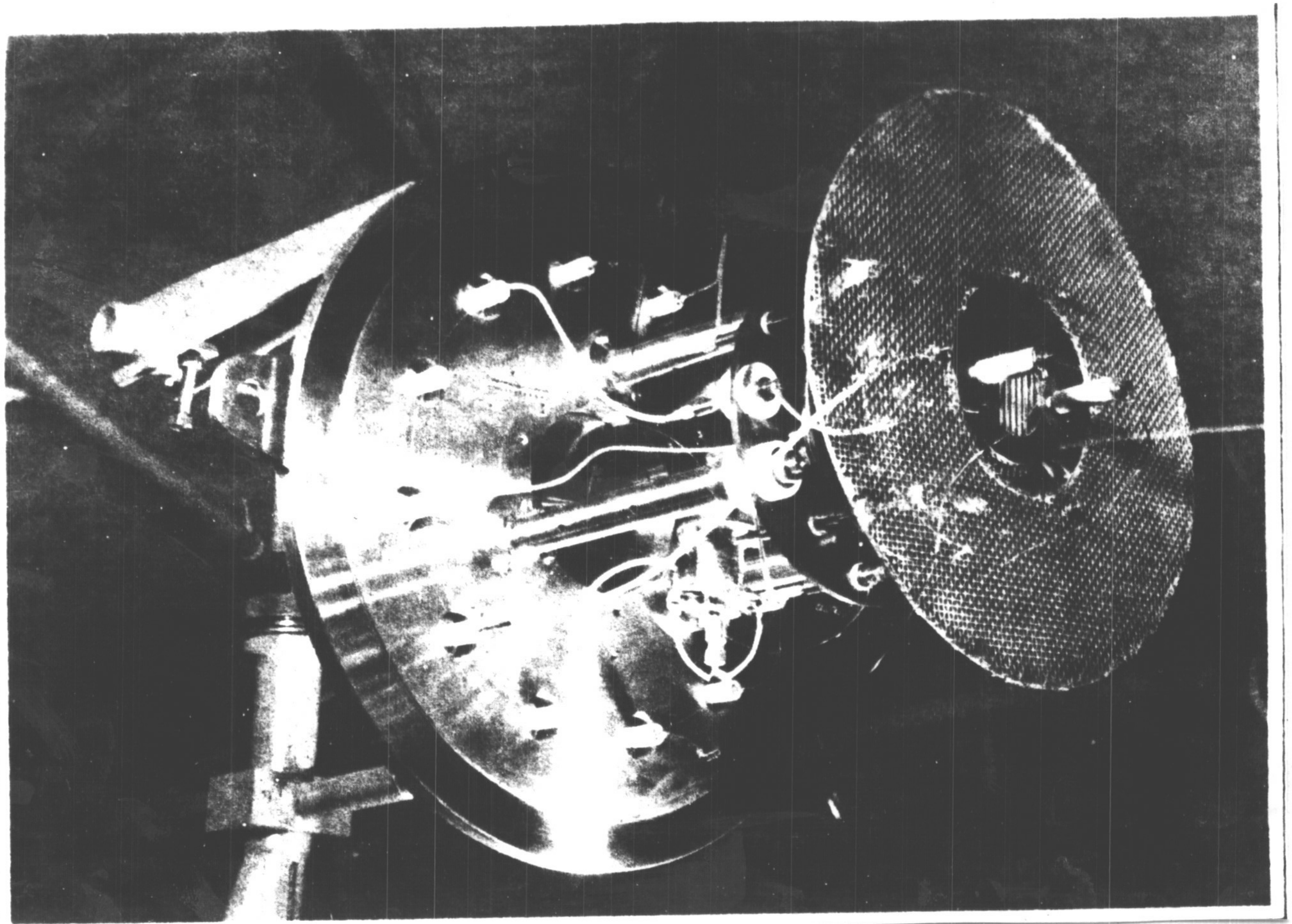

Figure 4

Mercury Ion Accelerator

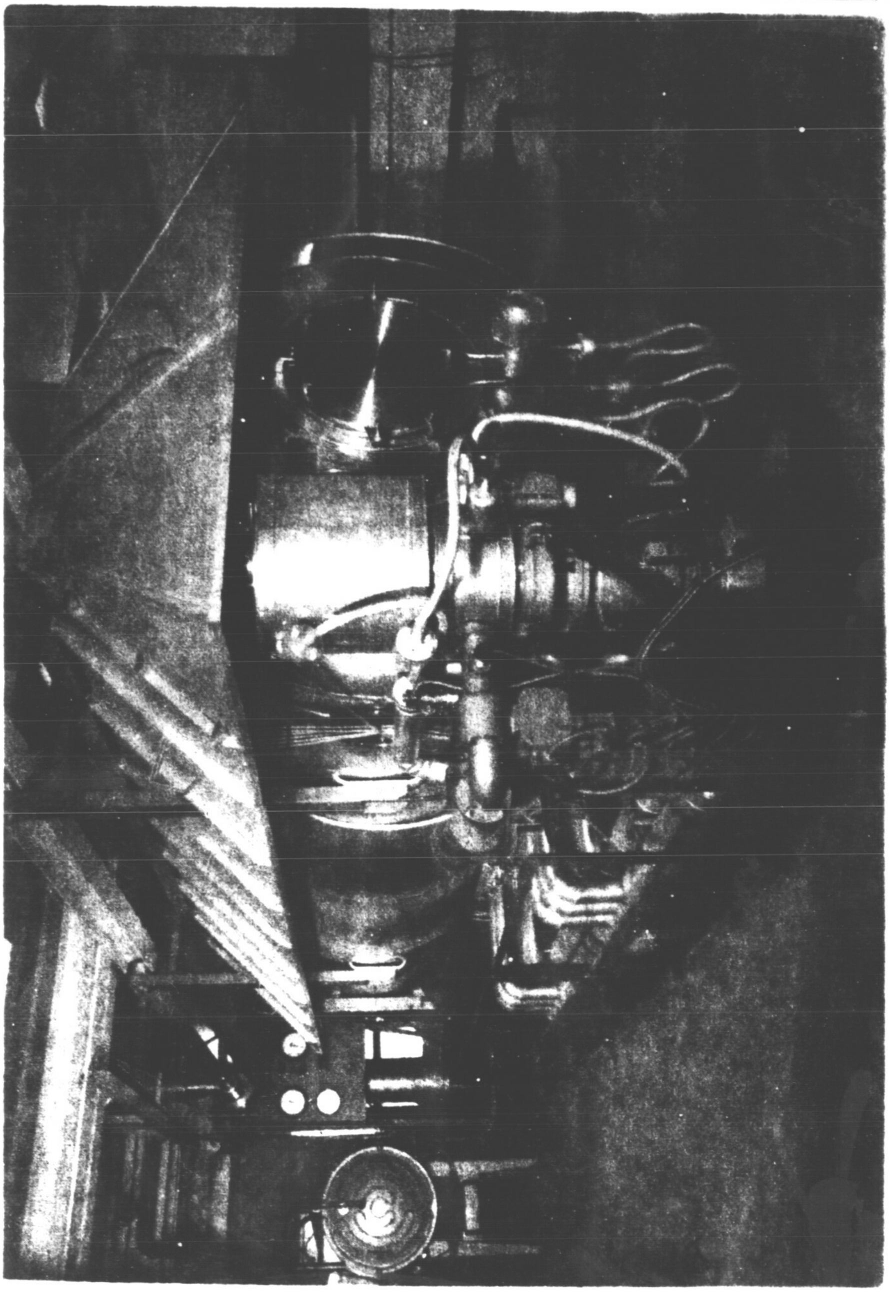

Figure 5

between the electrons and the metallic atoms. The extraction and acceleration of the ions is assured by means of two adjacent grids, and the bundle can be neutralized by means of a heated wire which emits electrons.

Performance and endurance experiments were carried out in an evacuated casing ($10^{-6}$ Pa),* which has an interior volume of 3.5 m3 which is sufficient to permit the study of the bundle and the behavior of the ions (Figure 5).

A detailed study of the operation has been carried out. This led to a description of the various characteristics as a function of the given parameters: mercury output, heating intensity of the filament, electric voltage, magnetic field. The latter is not a requirement. I would like to discuss the study of the ion bundle, which was sufficiently refined to take into account the importance of the wall effects.

The bundle was not neutralized by means of an electron contribution. Measurements of the electric current were carried out at various locations. This made it possible to establish the course of the ions, as is shown in Figure 6. It is variable depending on the value of the cathode potential. For very small values, the ions are intercepted in large numbers by the grid, and those which escape fall back on the grid and the casing. (Trajectory $\alpha$).

When the voltage is increased, the trajectories of the ions are lengthened and reach the wall of the casing (trajectory $\beta$). The ions only reach the target after a certain critical value is reached, which in this case lies in the vicinity of 3 kV (trajectory $\delta$). Then, the ion bundle is well developed. It is received completely by the target, and the casing receives nothing.

Figure 7 shows these results again and, in particular, shows the abrupt increase of the current received by the target. It should be noted that the numerical values are valid for a given geometry, and also under the condition that the pressure is small enough, so that the ionization of the residual gases can be neglected. This was the case for the measurements under consideration; the pressure within the casing was $10^{-6}$ Pascal.*

When the ion generator is operating without the neutralization filament, the radiation of the generator on the target is completely

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* Pa = Pascal = 10 bars

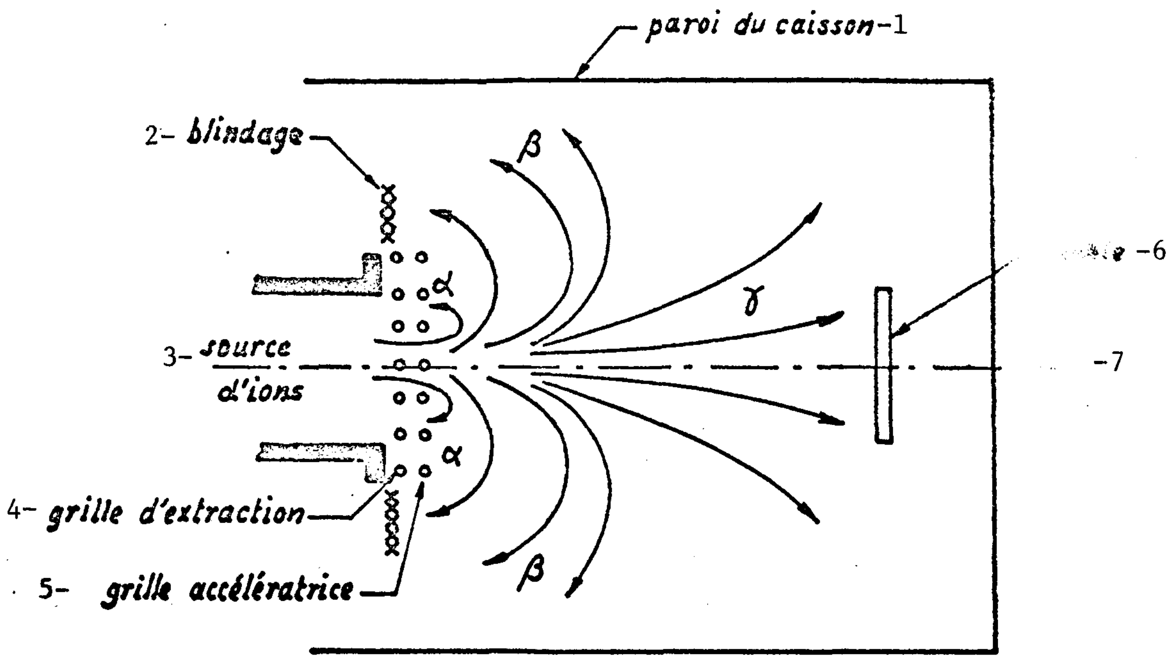



Figure 6

Mecury Ion Accelerator: Ion Trajectories at the Output of the Source

(1) Casing Wall; (2) Protection; (3) Ion Source; (4) Extraction Grid; (5) Accelerating Grid; (6) * ; (7) *

negligible, and the power which the latter receives due to ion impact can be measured by the extent of its heating. This can be compared with the electric power supplied to the ions.

The former is the product of the heating capacity and the heating rate. The latter is the product of the accelerating voltage and the current. /4

The results are shown in Figure 8 and show an excellent agreement between the two methods. This indicates that there is a good collection of ions on the target, as well as the absence of reflections or noticeable reemissions.

The neutralization of the bundle does not present any particular difficulties. It is simply obtained by means of a tantalum filament placed 50 mm away from the accelerating grid.

* Translator's note: Not legible in original foreign text.

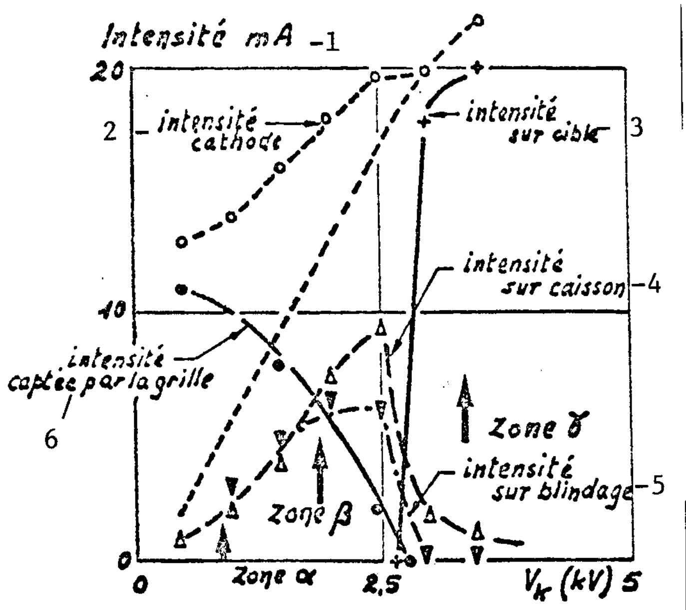



Figure 7

Mecury Ion Accelerator: Influence of the Accelerating Voltage on the Auto-Neutralization Phenomenon.

(1) Intensity; (2) Intensity on the Cathode; (3) Intensity on the Target; (4) Intensity on the Casing; (5) Intensity on the Protection Unit; (6) Intensity Captured by the Grid.

Experiments over long periods of time have been carried out with this apparatus. After running for 100 hours, a detailed examination of the various components showed that extended operation would have been possible. The performance was as follows:

Average mercury output . . . . . . . . . . . . . 65 $\mu g.s^{-1}$

Useful output . . . . . . . . . . . . . . . . . . .0.7

Ejection velocity of ions . . . . . . . . . . . 54 $km.s^{-1}$

Thrust (estimated) . . . . . . . . . . . . . . 2.5·$10^{-3}$N

Specific Impulse . . . . . . . . . . . . . . . . 3800 s

Total output . . . . . . . . . . . . . . . . . 0.36

Total power . . . . . . . . . . . . . . . . . . . 250 W

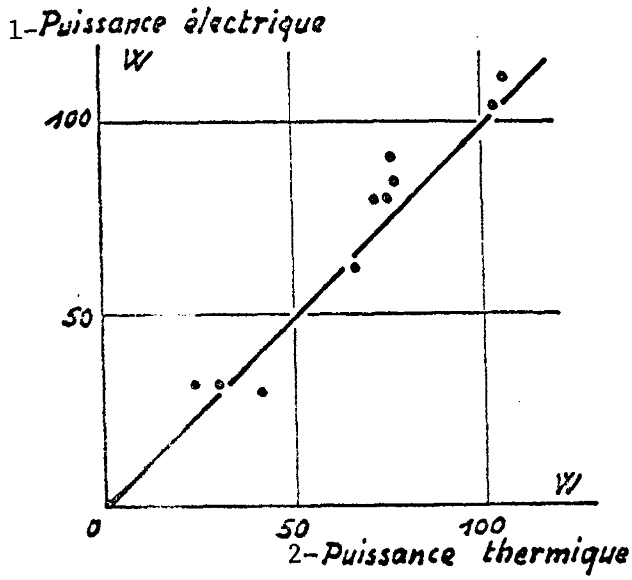



Figure 8

Mercury Ion Accelerator;
Electrical and Thermal Determination of Power

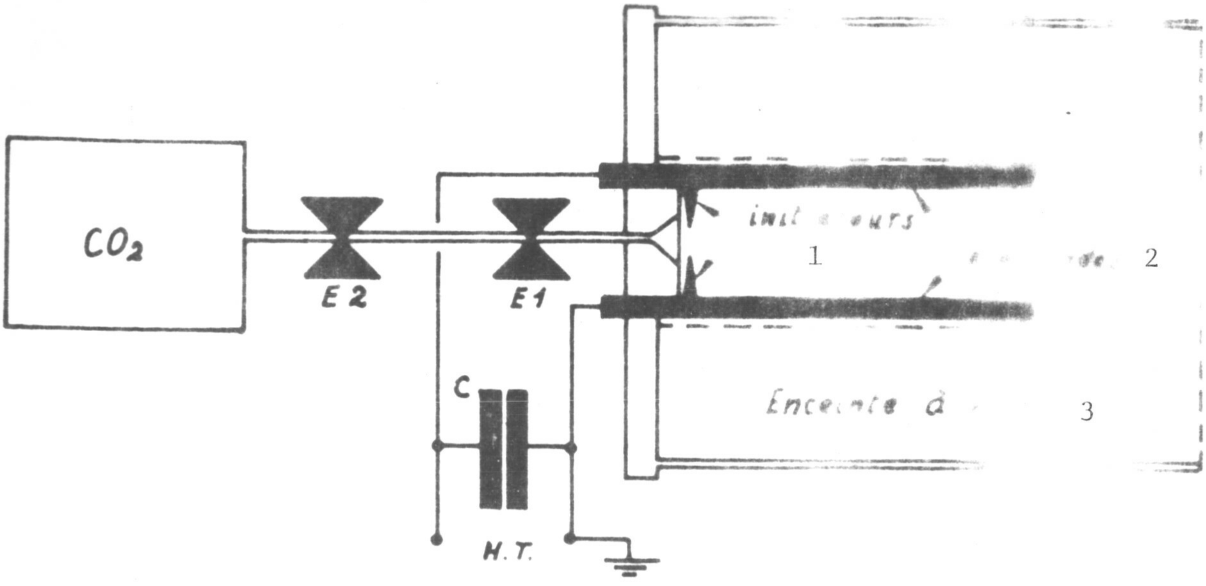
(1) Electrical Power; (2) Thermal Power

It can be assumed that a propulsion unit of this type could be built very rapidly in order to satisfy the needs of certain space missions with orbits in the vicinity of the earth, such as orbit corrections or maintaining synchronous satellite orbits.

## RAIL-TYPE PLASMAGUN

The device which was built was constructed in order to carry out detailed studies on the propagation of the discharge (Figure 9). This is done essentially by electrical measurements, but also in part by optical means.

The first experiments which were carried out consisted primarily of measurements of the magnetic field (Ref. 7). If the discharge is considered as a conducting bar in the first approximation, it is easy to derive its propagation velocity from measurements of the axial and transverse components of the field induced by the circuit (Figure 10). The phenomenon is complicated by the presence of a residual discharge at the level of the initiators and by an electric current, which cannot be neglected, which fills the entire space between the initiator and the discharge. Measurements of the local intensity by means of Rogowski coils made a precise definition of this phenomenon possible (Figure 11). It was thus possible to correct the measurements of the propagation speed of the discharge.



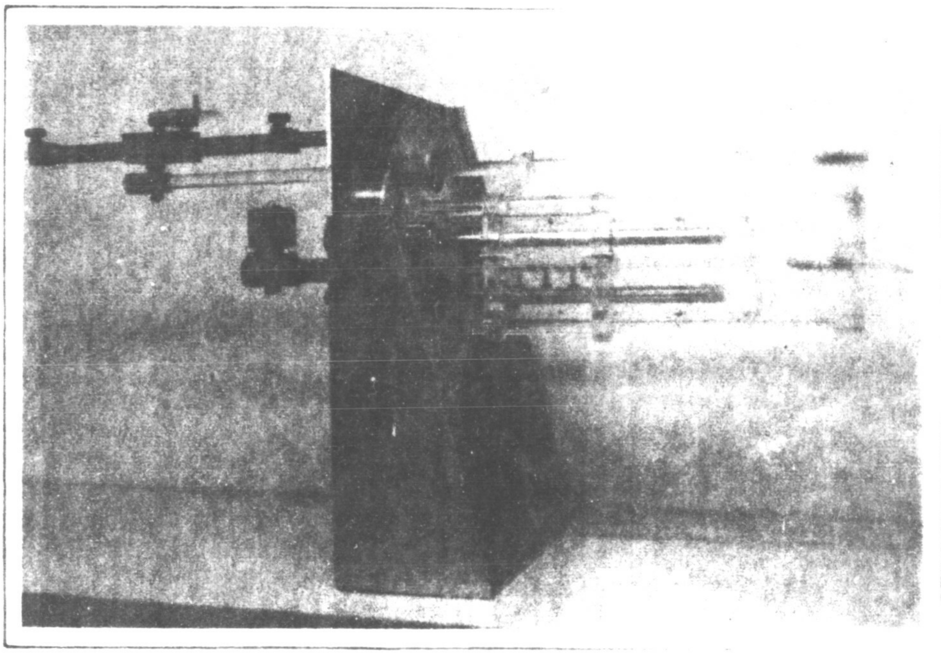



Figure 9

Rail-Type Plasmagun

(1) Initiators; (2) Electrodes;
(3) Illegible in Foreign Text.

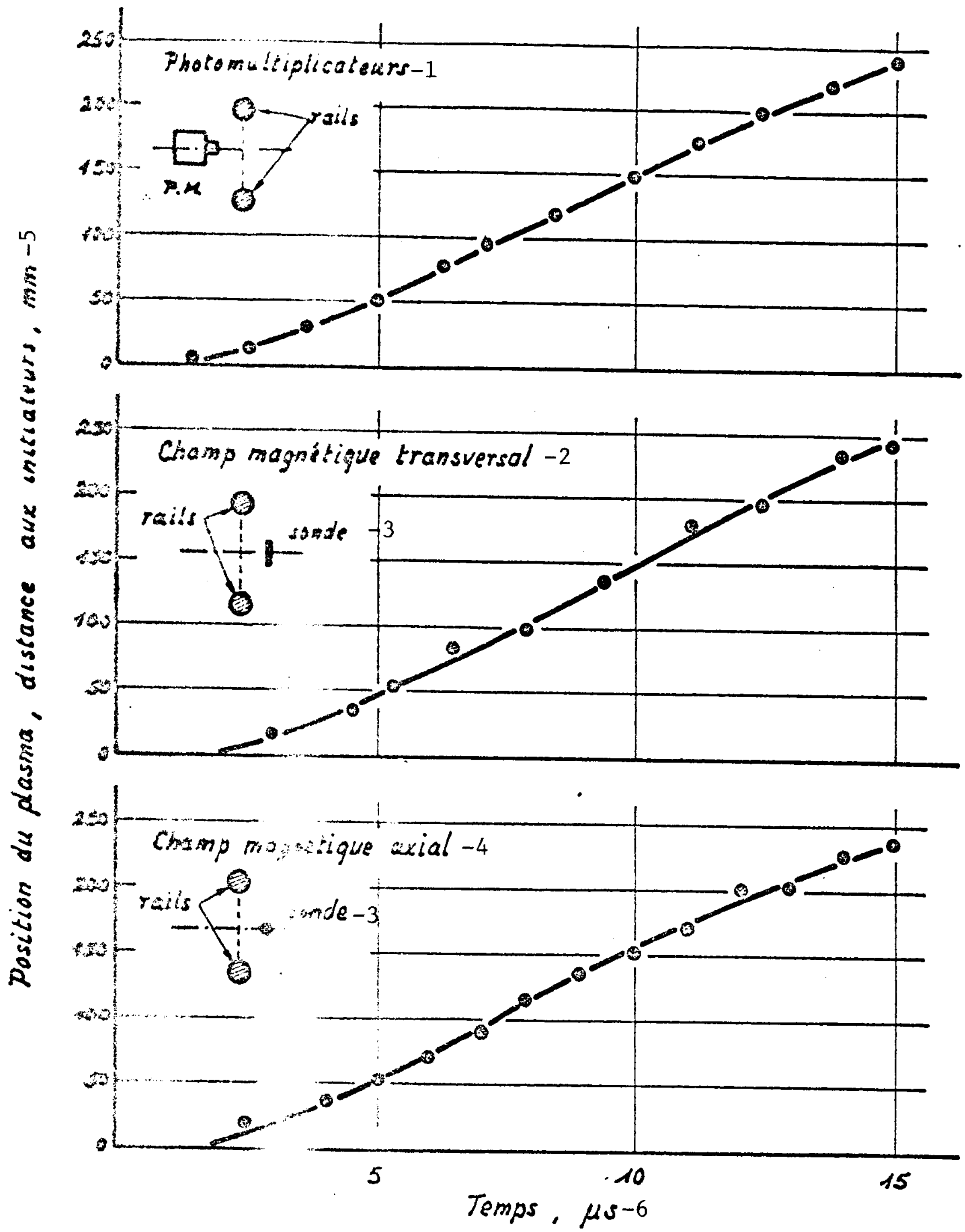



Figure 10

Cannon Type Plasmagun.
Comparison of Methods for Measuring the Speed of the Plasma

(1) Photo Multipliers; (2) Transverse Magnetic Field; (3) Probe; (4) Axial Magnetic Field; (5) Position of the Plasma, Distance to the Initators, mm; (6) Time

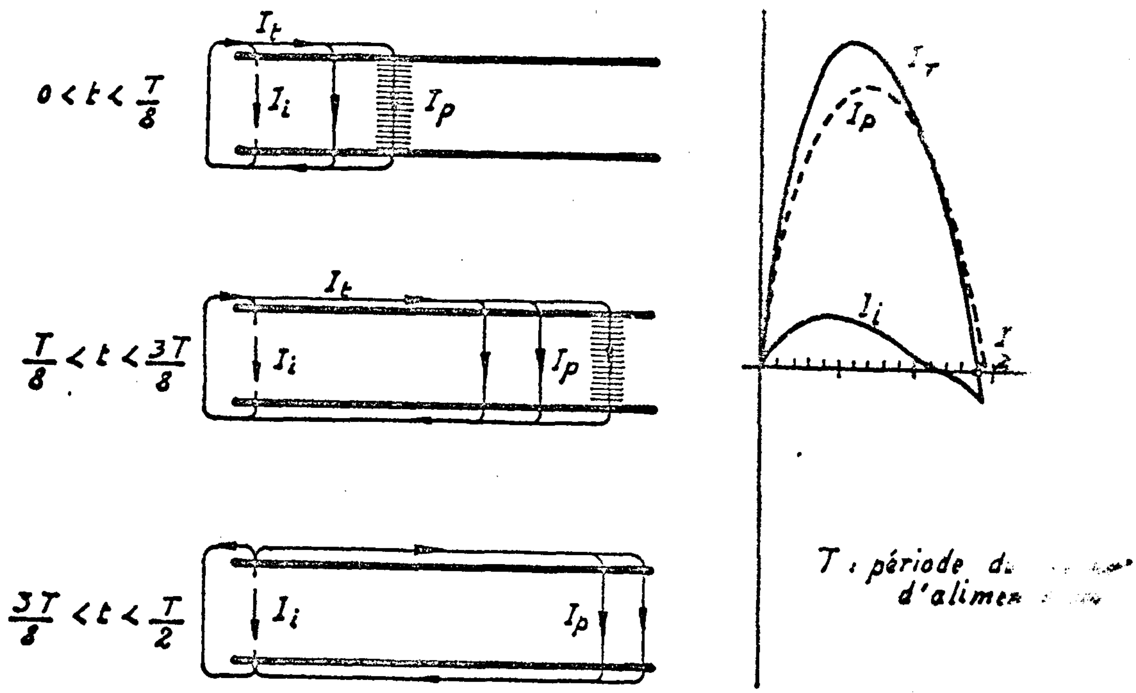



Figure 11

Rail Type Plasmagun
Growth of the Plasma Bulge in the Course of the First Half-Period
(1) $I_t$: Total Intensity; (2) $I_p$: Intensity of the Plasma current; (3) $I_i$: Intensity at the Level of the Initiator; (4) T: Period of the Supply Current

Nevertheless, it was impossible to determine the acceleration period of the plasma created by the discharge in this way. The propagation speed was found to be constant along the entire length of the conductors. /5

The use of photomultipliers results in an exact localization of the discharge and resulted in an exact picture of the acceleration process which takes place within a very small fraction of the period (approximately 2 μs). This brief duration of the acceleration can be explained by the very great predominance of the electric forces over the aerodynamic forces which could introduce the friction forces. It was possible to determine the direction of the discharge (Figure 12) which is inclined

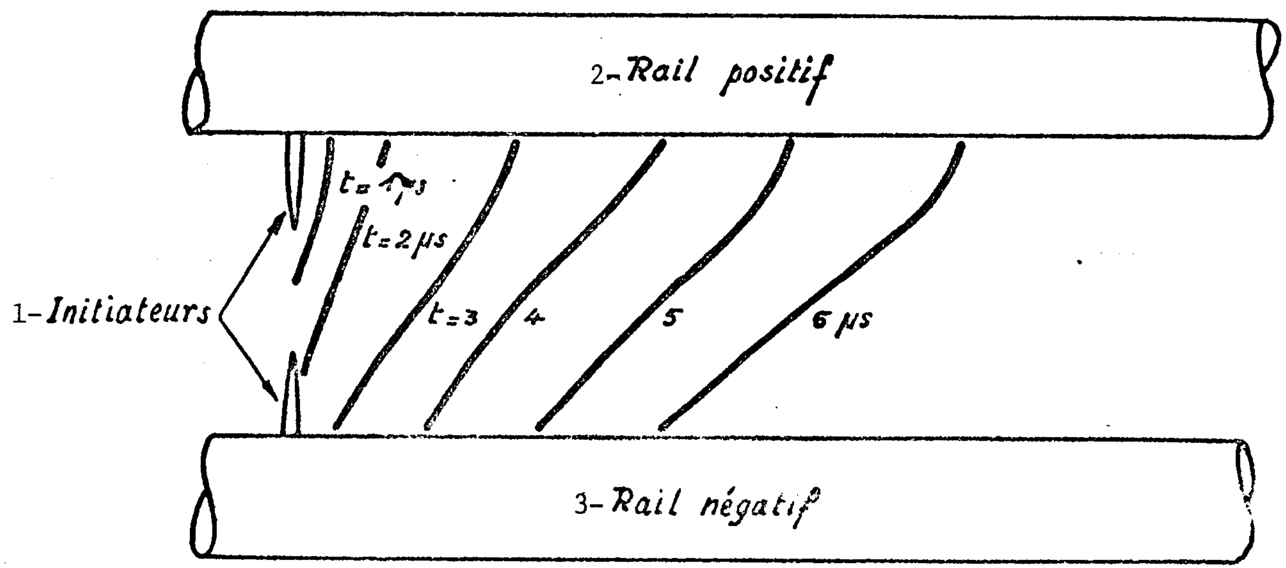



Figure 12

Rail Type Plasmagun: Deformation of the Discharge at the Beginning of Firing.

(1) Initiators; (2) Positive Rail; (3) Negative Rail.

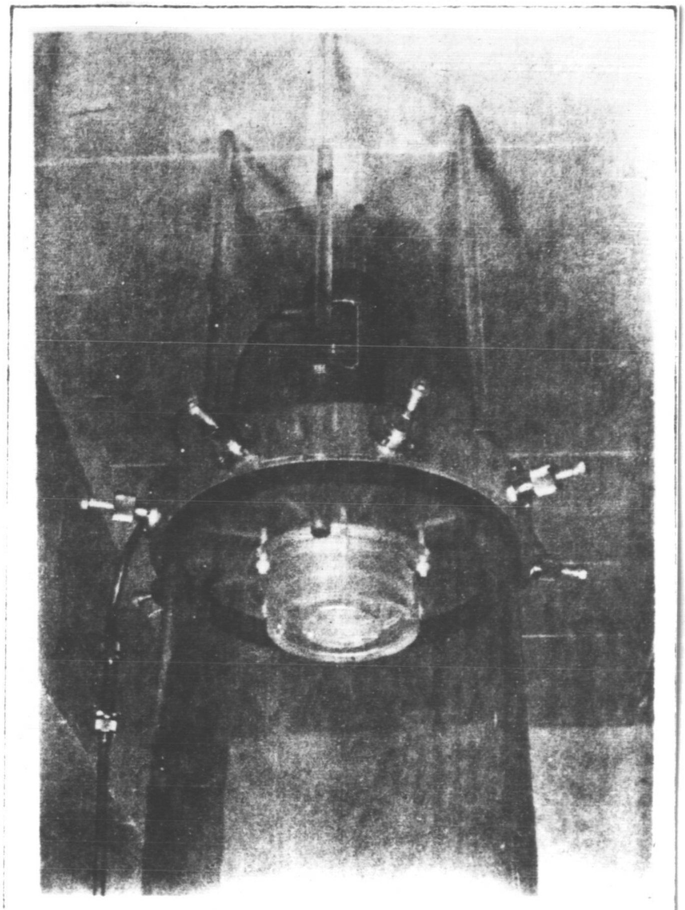


Figure 13

Argon Travelling Wave Accelerator

with respect to the axis. This inclination changes sign with the polarity of the electrodes, due to the effect of Hall forces.

These experiments in particular showed the discrepancy between the true phenomena and the simplified model used initially, whereby the discharge was represented as a rigid plasma column which is accelerated along the entire length of the rails.

In order to determine all the quantities mentioned using this experimental device, it was necessary to perfect very rapid measurement methods, which are adapted to the detailed study of plasmas in motion.

## PLASMA ACCELERATOR WITH A SLIDING FIELD

This type of propulsion unit is based on the removal of the conducting medium, which is the plasma, by Foucault currents,

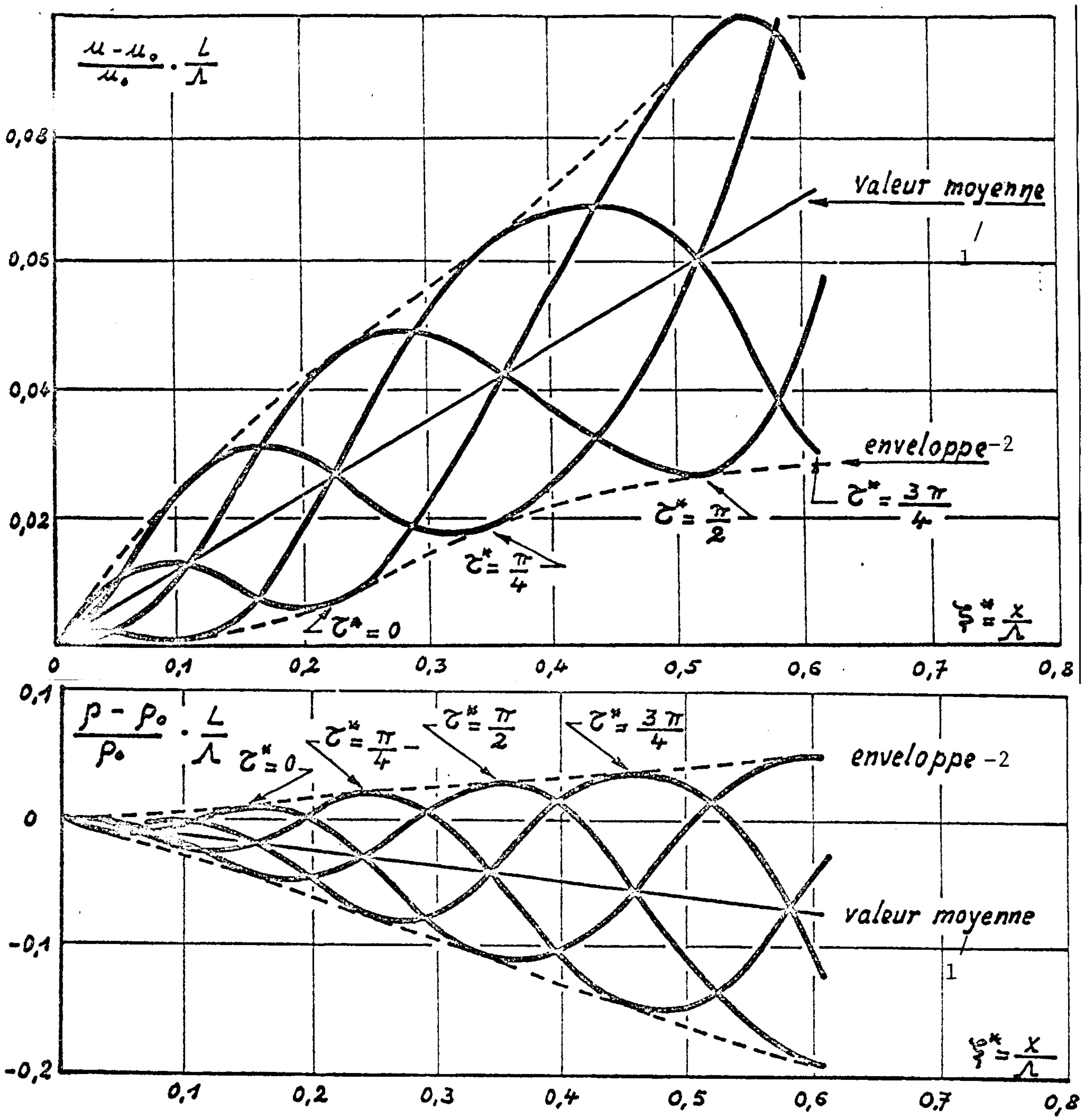



Figure 14

Travelling Wave Accelerator
Axial Growth of the Velocity and of the Volume Mass.
(Linearized Calculation $\gamma = 5/3$, $M_0 = 3$, L = Length of the Accelerator, $\Lambda$ = Wave length)

(1) Average Value; (2) Envelope

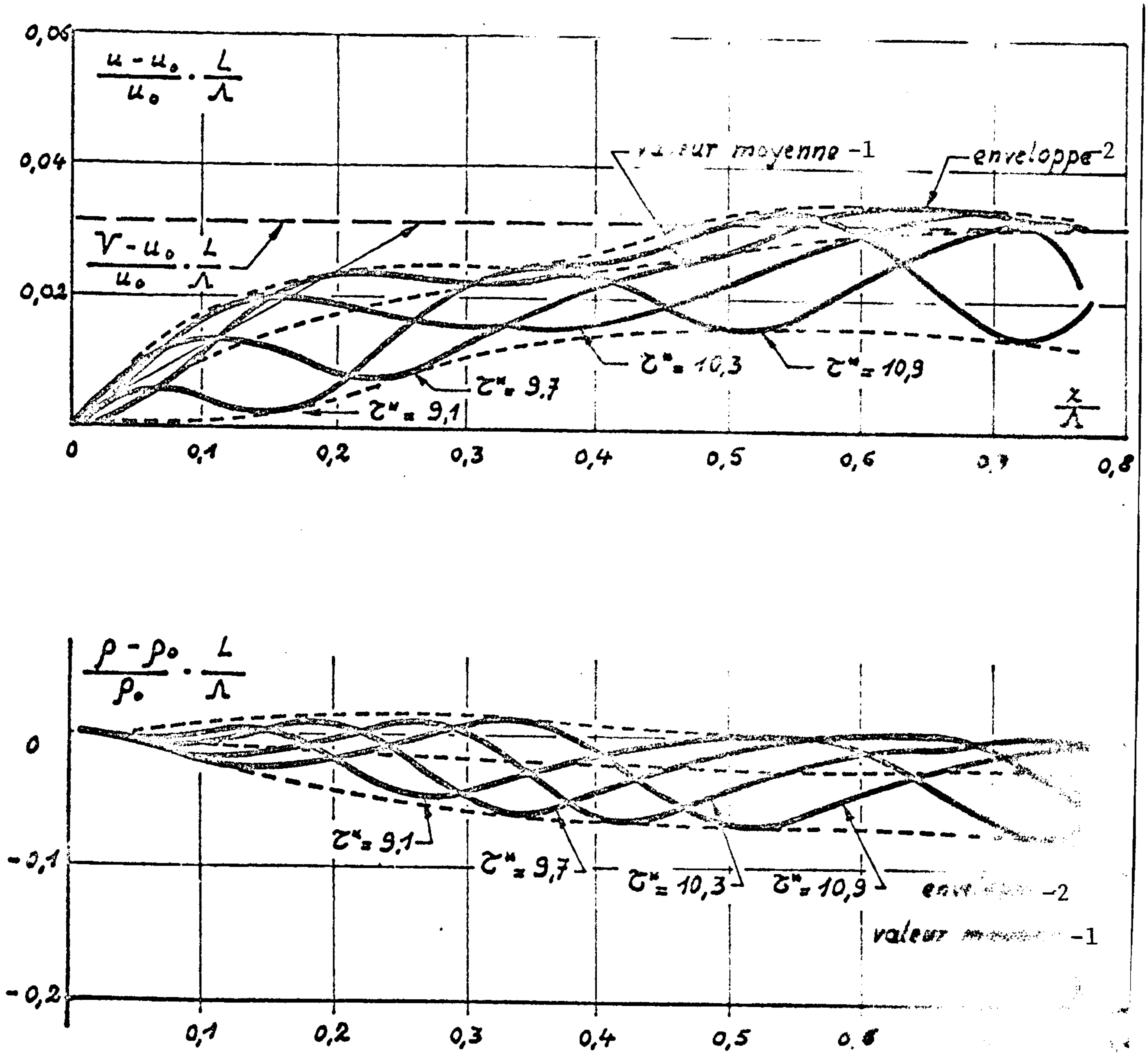



Figure 15

Travelling Wave Accelerator
Axial Growth of the Velocity and of the Volume Mass.
(Semi-linear solution which shows the saturation (?) of the increase in velocity)

($\gamma = 5/3$, $M_0 = 3$, L = length of the accelerator, $\Lambda$ = wave length)

(1) Average value; (2) Envelope

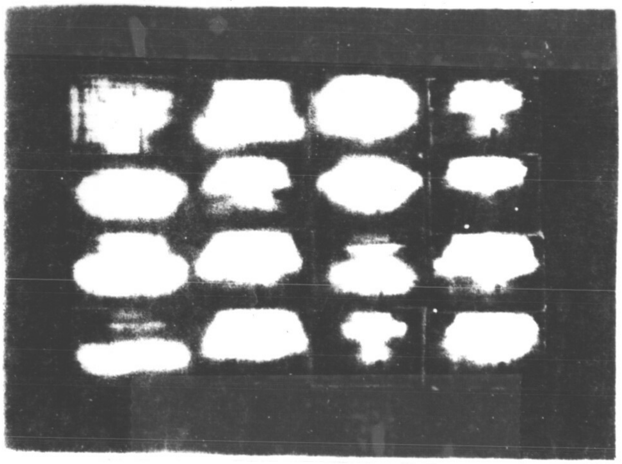


Figure 16

Travelling Wave Accelerator:
Successive Views at 0.5 μs Intervals of the Plasma
Output by the Accelerator

which produce a variable magnetic field.

The latter is produced by means of coils, which are supplied by multiphased currents having a frequency of 100 kc. They are arranged in the manner shown in Figure 13.

The operational theory of such an accelerator was based on the assumption of an annular channel having a constant height, which is small with respect to the average radius and the length of the channel. The periodical components of the sliding field cause alternating forces within the plasma which are converted into successive swellings, which are confined by the magnetic field.

The linearized theory, in which one assumes weak electromagnetic perturbations, (Ref. 8,9, 10), predicts this pulsed structure of the jet. This is shown in Figure 14, which shows the variations of the speed and the volume mass of the plasma as a function of the abscissa, which is related to the wave length:

$$\Lambda = \frac{2\pi V}{\omega} .$$

In this case it is 0.1 m.

In reality, the theory is insufficient when the sliding of the plasma with respect to the field becomes small. An improved theory

Figure 17

Mercury Pump During Operation

leads to the curves shown in Figure 15, which still show the cellular character of the outflow, but show a saturation which is reached quite rapidly, since the limiting velocity is obtained for a distance less than one wave length.

In reality, the phenomenon takes place more rapidly. This is due to the very small relative influence of the aerodynamic forces, as was the case for the rail-type plasmagun. However, the experiment confirmed these theoretical results. It was carried out with a jet from an argon plasma accelerator (Ref. 11), which had an average diameter of 9 cm and a length of 7 cm (Figure 13). An electronic camera was used to obtain photographs at one-half microsecond intervals. /6
The average ejection velocity was 25 to 30 km per second. Figure 16 shows the sequence of plasma swellings, and it may be readily ascertained that the frequency of the phenomenon is equal to twice that of the supplied current, because it is determined by the square of the magnetic field.

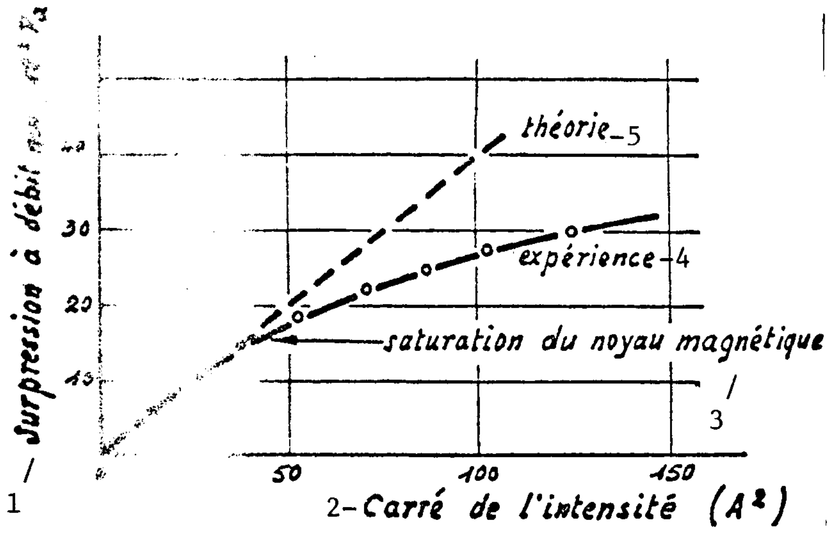



Figure 18

**Mercury Pump:**
Suppression at Zero Output

(1) Suppression at Zero Output; (2) Square of the Intensity; (3) Saturation of the Magnetic Core; (4) Experiment; (5) Theory

The same investigation was carried out using photomultipliers. In order to make the zones appear sufficiently luminous, two small spheres were placed diametrically opposite each other within the jets, at different levels. Shock waves were produced on them. The velocity of the plasma was derived from the delay between the illumination of the two shock waves.

These investigations showed very well that the velocity of the plasma is that of the sliding field, under the condition that the mass flow is less than a critical value. If this is not the case, the accelerator is uncoupled, in the sense of the uncoupling of an asynchronous motor.

This is a phenomenon which is quite analogous to the classical thermal blocking of a focus. In the present case, the velocity is reduced to 4 km per second, which corresponds to an aerodynamic expansion of the fluid heated by high frequency waves. The latter produce no acceleration, but their energy is entirely absorbed by the plasma in the form of heat.

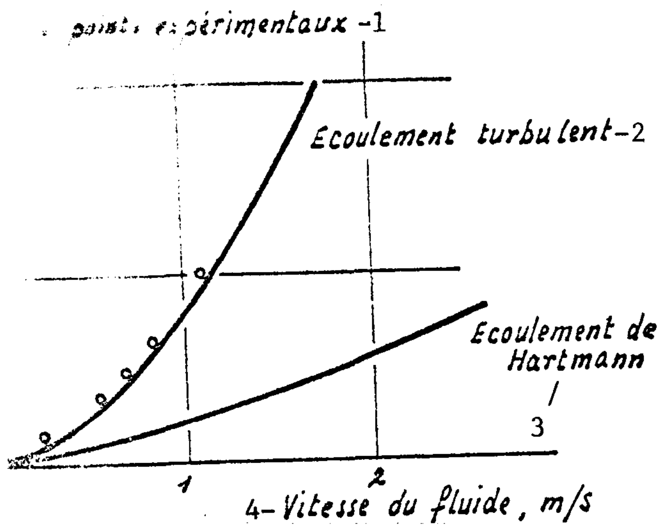



Figure 19

Mercury Pump:
Variation of the Charge Loss With Output

(1) Experimental Point; (2) Turbulent Outflow;
(3) Hartmann Outflow; (4) Speed of the Fluid

Before we examined the transfer mechanism of the electromagnetic wave energy to a conducting medium, we designed a similar device in the form of a mercury pump (shown in Figure 17). This apparatus shows the great importance of friction phenomena (Ref. 12). For zero output, the overpressure delivered by the pump is exactly equal to the one predicted by theory, at least when the axial iron core does not reach magnetic saturation. (Figure 18).

As soon as the mercury circulates in the pump, very high charge losses appear, which are closer to those corresponding to turbulent outflow than those which result from Hartmann's law (Figure 19).

These charge losses have an effect on the yield, due to the very harmful heat transfer. This fact led to the design of a plasma accelerator which was as short as possible, since it was clear that the length required to attain the limiting velocity is reduced.

End effects and the rapid decrease of the electromagnetic field at the outlet of the apparatus were found to be disturbances which were less serious than the heat transfer mentioned.

The device described above has already been constructed according to this principle. A second accelerator, designed for quasi-permanent operation and which operates with sodium vapor (Figure 20), has been constructed in a similar way. The time of operation is a few seconds. It is only limited by the heating of the coils.

Due to the principle involved, travelling wave propulsion units are suitable for a power level on the order of 100 kW at least. Their yield is on the order of 40%, but becomes very poor at low power due to the considerable relative increases of heat losses.

## ELECTRIC ARC PROPULSION UNIT /7

Even though research on arcs carried out at the ONERA was done primarily in the investigation of air heaters (Ref. 13, 14), arc propulsion units were nevertheless studied due to thier interesting possibilities in the specific impulse region from 500 to 1000 seconds. They are also of interest due to their simplicity of construction and simplicity of operation. The analysis of their operation and the study of their stability were carried out.

Essentially, argon (Ref. 15) and helium were used as propellants in apparatus which were cooled by water, necessitated by the long operational times. The simplicity of the principle for these apparatus does not call for a great deal of fundamental research. The experiments which were carried out in this connection are more technological than the preceding experiments. We should mention the measurements of the speed of rotation of the arc, experiments on the operation in a vacuum, and the distribution of the heat losses among the various parts of the generator.

The arc which jumps between an axial cathode and an anode in the form of a convergent tube clearly has the appearance of a spiral which is rotated by means of an axial magnetic field, such that the mass is swept out of the chamber and, at the same time, the wear of the electrodes is reduced by distributing the arc over their peripheries.

The measurement was carried out using photomultipliers and cinematography, at a rate of 8000 frames per second.

A preliminary determination of this rotation speed was made, by writing down the equation for the stationary equilibrium of the arc under the influence of electromagnetic and aerodynamic forces.

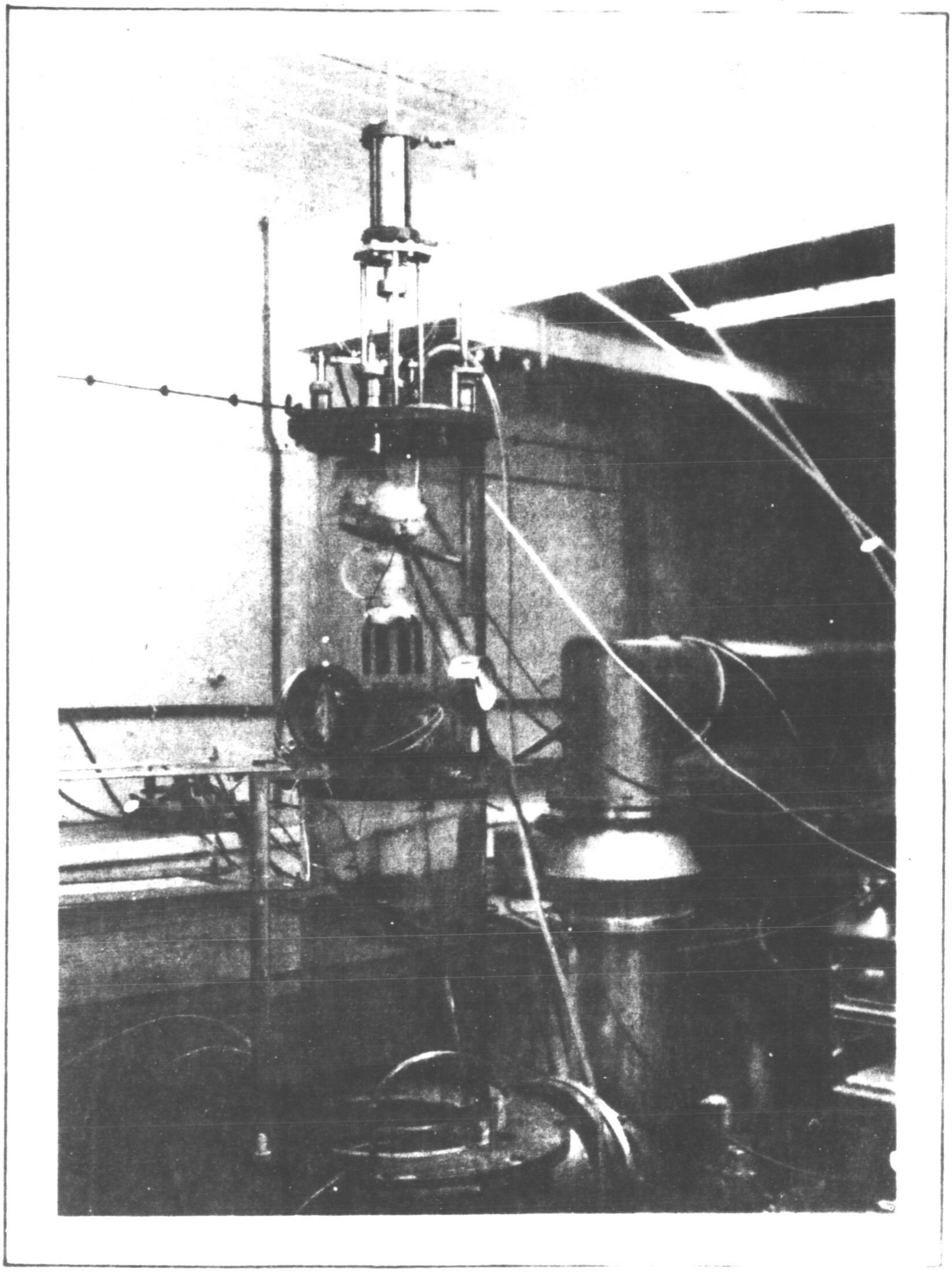


Figure 20

Sodium Travelling Wave Accelerator

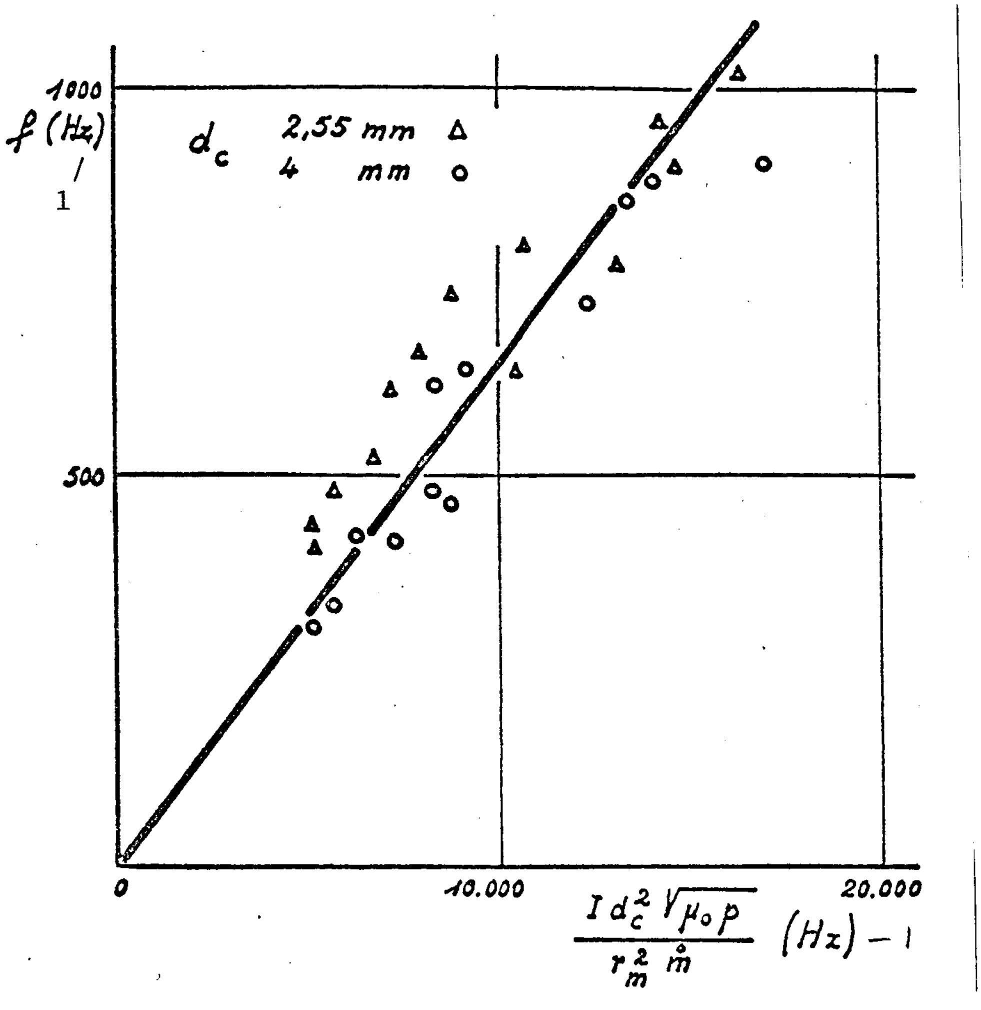



Figure 21

Increase of the Speed of Rotation of the Arc

(I: Intensity, $d_c$: Diameter of the cathode, $\mu_o$: Permeability of vacuum, p: Pressure, $\tau_m$: Average radius of the assembly, $\dot{m}$: Mass output)

(1) Cycles

O.N.E.R.A. CASINGS FOR PROPULSION UNIT EXPERIMENTS CARRIED OUT IN A VACUUM

| Designation | A.611 | A.612 | B.61 | B.63 | |
|---|---|---|---|---|---|
| Method | Large capacity vacuum chamber and air pump, mechanical pumping. | Chamber with diffusion pump, condenser. | Cylindrical chamber, diffusion pump, condenser. | Large chamber, diffusion pump, condenser, thermal wells. | |
| Extracted mass yield (gr/sec) | 1 to 100 | $2.10^{-2}$ to $1.10^{-1}$ | $2.10^{-5}$ to $2.10^{-2}$ | $5.10^{-4}$ to $5.10^{-1}$ | |
| Surface of the condenser ($m^2$) | | 10 | 5 | 73 | 1 |
| Type of cooling fluid | Water | $N_2$ (77°K) | $N_2$ (77°K)<br>He gas (20°K) | $N_2$ (77°K) | He gas (20°K) |
| Pressure in the chamber (Pascals) | 1 to $10^2$ | $10^{-4}$ | $10^{-6}$ | $10^{-4}$ | $10^{-6}$ |
| Volume of the chamber ($m^3$) | * | * | 3.5 | 55 | |

* Translator's note: Illegible in original foreign text.

Figure 22

A relationship between the frequency of rotation and the non-dimensional number is obtained

$$\frac{I \cdot d_c^2 \sqrt{p \mu_0}}{\dot{m} \, r_m^2}$$

which, as experiments show, may be applied satisfactorily, as Figure 21 shows. I is the current of the arc, $d_c$ is the mean diameter of the cathode, p the pressure, $\mu_0$ is the permeability of vacuum, $\dot{m}$ the mass yield and $r_m$ the mean radius of the arc.

## CONCLUSION

This brief summary of work carried out at the ONERA in the field of electric propulsion shows that results have already been obtained which enable us to define materials which satisfy a specific requirement. I do not mean to say that all the problems have been solved. A great effort must be made to arrive at a complete understanding of the phenomena and also to collect knowledge which is sufficient for the construction of propulsion units, which must function without failure over long periods of time. /8

The ONERA is equipped with a number of vacuum installations, which makes it possible to carry on these investigations.

Figure 22 summarizes their characteristics in the form of a general table. This shows the variety of the installations.

These apparatus lend themsleves to experiments with propulsion units of all types, under widely varying conditions. Great progress may be expected in the future.

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